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Aircraft Structural Design Geared for High Reliance on Analysis for Acceptance

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Abstract

The results of an initial study of key structural areas for the design of a state-of-the-art composite fighter wing are used to highlight the fundamental changes that can be expected when aircraft acceptance considers analyses as a prime tool for demonstrating that the structure is safe for flight. For analyses to become the primary basis for accepting an aircraft structural design, a high level of confidence must be developed for the analysis methods used. The strategy investigated here is to maximize this confidence level in the use of probabilistic aircraft structural design methods rather than conventional deterministic methods. In a recent advanced lightweight aircraft structure development program, an advanced design of composite materials was created, using the latest deterministic design and manufacturing features. This composite fighter design effort provides a good benchmark for exploring the potential differences in design and testing that can be expected if probabilistic design methods are used to establish high confidence in design analysis. This present study chose two key aspects of the wing on which to investigate these differences. First examined is a local model of the cobonded joint attaching the wing box cover to the wing spars. For the second, the post-buckled design of the wing box cover is examined while subjected to the most severe maneuver load case.

Introduction

A significant level of interest has developed in recent years in the possibility of developing analysis capabilities with sufficient fidelity that they could be evolved into the primary source of information leading to the qualification or certification of a new aircraft structure for flight. In this design and acceptance environment, structural testing would evolve to a role of assuring correct analytical evaluations, rather than providing final clearance for flight using the traditional full-scale structural article limit load/ultimate load testing approach, especially of large final articles.

In this environment, testing would evolve into a new role of developing a sufficient database to model the way structure could vary over a production run. Testing would be used to fine-tune the analysis methods and models. These analyses would then provide the final check for clearance of a new design. The key to success is developing various procedures to raise analysis precision to this level. This effort explores the use of probabilistic methods in aircraft structural design to achieve the needed analysis precision. Examination is made of how test programs supporting the analyses would be restructured and, hopefully, reduced in cost when restructured to support analyses-based clearances.

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Use of probabilistic methods in design has long been considered an intriguing way of introducing the unavoidable uncertainties in the characterizations of all our physical descriptors of aircraft structure. They allow the characterization of the uncertainties in modeling, materials, structural geometry, loads, etc. in the analyses such that the uncertainty of the analyses can be observed and addressed. The primary technical drawback to the use of probabilistic methods, for a long time, was the Monte Carlo methods traditionally used for calculating the probabilities of occurrences.

By their very nature, aircraft structures must have very low probabilities of failure in order to be acceptable for flight. Thus, the use of traditional Monte Carlo methods demanded a large number of analysis evaluations corresponding to all the variations needed for the design variables. Many evaluations were needed to generate enough failure cases to adequately define the "tail" of the probability of failure curve where acceptable values of aircraft structural failures reside. This would now be further aggravated by the large increases expected in analysis model complexity such as structural finite element analysis (FEA) models as the fidelity is increased to meet the objective of analysis carrying the burden of clearance for flight.

Developments in probabilistic methods have changed the analytical environment needed to calculate probabilities of failure of very reliable structure such as that found on aircraft. These methods, outlined in this paper, have the ability to project functional representations of the probability of failure with few analytical evaluations, as compared to that required by the older Monte Carlo methods. These methods, as shown in this paper, make the concept of characterizing structural failure in terms of probability of failure a practical reality.

The New Design Process

As the concept of probabilistic methods-based design is now computationally practical, the whole structural design process can be reconsidered. One outcome, examined here, is the restructure of the design process around assessment of structural viability, by reducing the analytical projection of failure probability to an acceptably low value. The traditional test program to support design acceptance can now be changed. Rather than demonstrate structural adequacy by overloading single test articles with test programs using excessive loads, the tests can be geared to develop adequate understanding of the variations in the design variables and quality of the analytical modeling. Using that understanding, a probability of failure can be designed into the structure that can account for both modeling errors and design variable errors. Use of this concept is examined by applying probabilistic design methods to the key design variables of an example wing.

To understand how the structural design process may be restructured, a design research program led by Southwest Research Institute, Structural Engineering Department, with Boeing - Military Aircraft and Missile Systems, was executed to examine, using a state-of-the-art wing design as a benchmark for comparison, how restructuring can be formulated. This paper documents some of the observations and findings of that program, and some of the implications they offer in moving the burden of structural acceptability to analyses. The aircraft structure used was a composite wing designed under an advanced aircraft structures development program, whose purpose was to identify structural design concepts and manufacturing processes that could lead to more unitized design, and assess their payoffs in application. This structure was deemed a good candidate because it represents the state-of-the-art in aircraft design, has high quality state-of-the-art computational models available, and has available key experimental component test data.

The reformulation of structural design into a form geared for high reliance on analyses uses probabilistic methods as its basic building block for characterizing the acceptability of the analyses. Testing supports the development of the probability of failure calculations. The design process then becomes an evolution of details and basic models into analytical models of increasing detail and sophistication, with each level of model evolution building on the previous level.

Two levels of design detail in wing structure were investigated. First studied was the local behavior of a cobonded joint representing an attachment concept that could be used between substructure and wing skins of modern composite wings. This represents an early level of detail that defines the basic elements of an overall

wing design. This was followed by a probabilistic design study of the wing box skin while carrying, in a post-buckled mode, a high g airload case that was pivotal in the advanced structures development wing skin design. This represents the higher levels of assembly and complete design analyses that would ultimately describe the probability of failure for the aircraft structure.

Investigations into Analyses of Structural Details

To illustrate how structural design can rely heavily on elemental analyses bolstered by support testing as the basic building blocks for acceptance of structural concepts, a cobonded joint was analyzed as one of the basic building blocks of the new wing structural design later used in this investigation. The cobonded joint is representative of the structure that connects the lower wing skin to the spar, as shown in Figure 1. This cobonded joint was chosen as a basic design element because it is a key structural link for many areas of the wing structural box used in modern composite wing design. It also had failure test data available, although limited, from the advanced structures development effort that provided the baseline for this program. This failure test data represents the kind of support testing that should be typical of this new probabilistic approach in design.

In current practice, structural certification of this kind of attachment area requires multiple test elements representing the significant details of the joint. Deterministic design allowables for these joints would be determined semi-empirically, using a combination of joint test data and analysis. This traditional approach requires significant amounts of time and resources. Also, the tests could require as much as a year and a half to complete, due to tooling and environmental conditioning requirements. In addition, if the design changes, the tests have to be redone, since the test articles have to reflect the final joint geometry. The probabilistic analyses of this effort demonstrate that a new approach is available. This approach allows safe prediction of the structural performance of these types of structural elements from basic data sets. In addition, since these sets are basic in most composite wing designs, they can be used without retest, as the design evolves. That is, the variability in performance of basic structural elements due to the combined variations of material properties, manufacturing processes, and environmental effects are analytically predictable based on experimental building blocks of the basic elements. This permits the testing of classes of elements to be considerably reduced or eliminated, the cycle time to be cut by 50 - 70% for future programs, and the avoidance of many retests as the geometry changes.

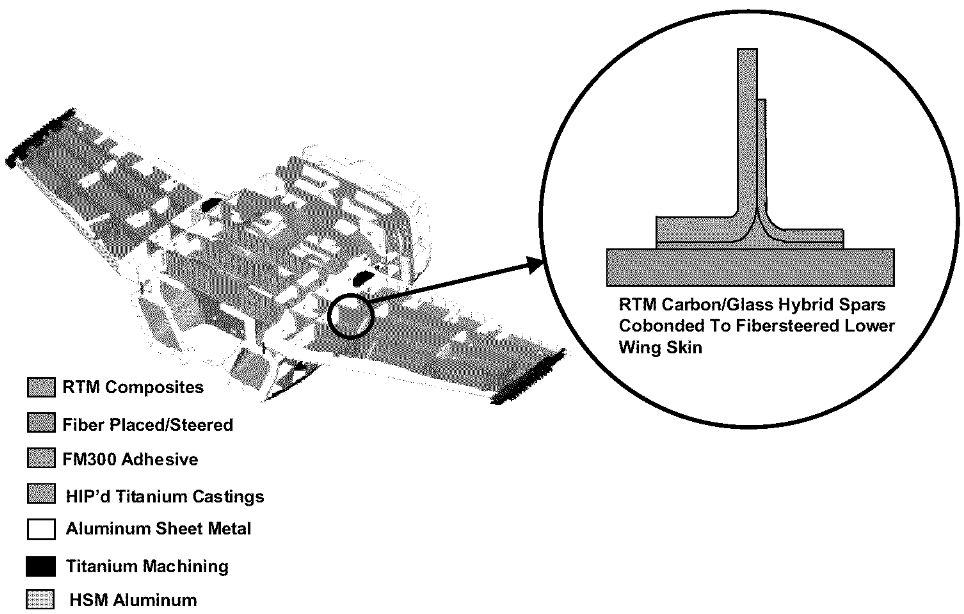

Figure 1 Wing and Cobonded Joint Structure

Boeing has performed destructive testing on joint specimens at cold, room, and elevated temperatures. Three replicate test structures were used at each temperature. The test procedure consisted of clamping the left and right edges of the flanges, and applying a pull-off load (P) until failure, see Figure 2. The value of the pull-off load was recorded.

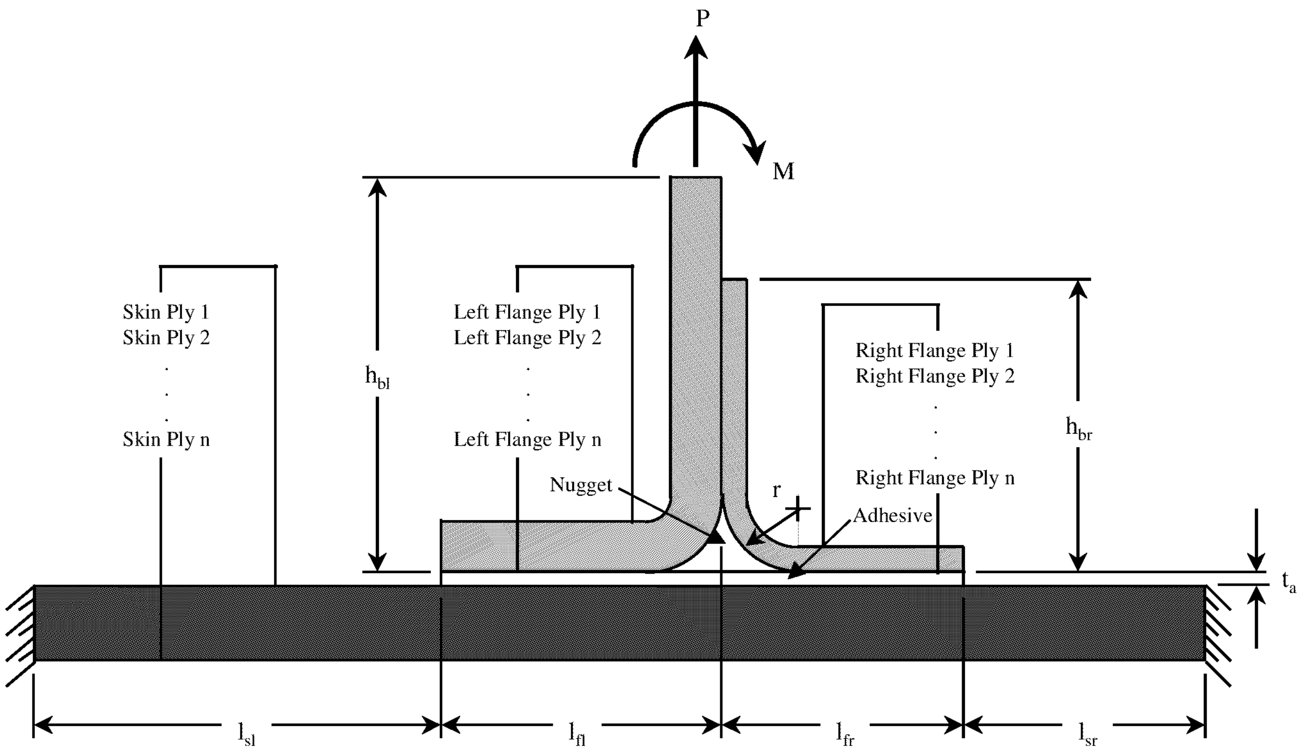

Figure 2 Schematic of Cobonded Joint Blade Model

The probability distribution function of the pull-off load was computed, using the Southwest Research Institute NESSUS™ probabilistic analysis software in conjunction with the THELMA nonlinear finite element software and the BLADEM preprocessor to THELMA. NESSUS™ is a general-purpose probabilistic analysis software that contains a library of statistical distributions, a selection of probabilistic analysis methods, and facilities for interfacing with deterministic mechanics programs.[1] THELMA is a nonlinear finite element analysis program specialized for generalized plane strain analysis of composite structures.[2] BLADEM is a preprocessor for THELMA that is specialized for composite joints such as that shown in Figure 2.[3] THELMA and BLADEM are proprietary Boeing codes.

The probabilistic model consists of 20 independent random variables, shown in Table 1. Dependent random variables are derived from the independent random variables. The dependent random variables are: for the Tape (E3, G23, G31, Nu31), and for the Cloth (E3, G23, G31, Nu31, Nu23). The coefficient of variation (COV) equals the standard deviation divided by the mean value. Material property data are available at cold, room, and elevated test temperatures. The data indicates that a truncated normal distribution is a good model.

Table 1 Independent Random Variables for Cobonded Joint Test Structure (75°F)

Composite Tape	**COV (%)**	**Distribution***
Modulus of Elasticity (E1)	3.2	TNORM
Modulus of Elasticity (E2)	2.0	TNORM
Shear Modulus (G12)	5.0	TNORM
Poisson's Ratio (Nu12)	11.9	TNORM
Ply Thickness	10.0	TNORM
Interlaminar Tensile Strength (S3)	7.8	TNORM
Interlaminar Shear Strength (T)	8.7	TNORM
Composite Cloth		
Modulus of Elasticity (E1)	6.9	TNORM
Modulus of Elasticity (E2)	5.0	TNORM
Shear Modulus (G12)	5.4	TNORM
Poisson's Ratio (Nu12)	41.5	LOGNORMAL
Thickness	1.5	TNORM
Interlaminar Tensile Strength (S3)	4.6	TNORM
Interlaminar Shear Strength (T)	8.4	TNORM
Adhesive		
Initial Shear Modulus (G)	12.8	TNORM
Tau Ultimate (τult)	9.1	TNORM
Gamma Ultimate (Γult)	22.9	TNORM
Nugget Radius (NR)	3.0	TNORM
Ply Thickness	10.0	TNORM
Interlaminar Shear Strength (T)	3.8	TNORM

*TNORM = truncated normal (at ± 3σ)

Failure is predicted computationally when the failure index exceeds 1.0. The failure index is defined as

$$FI = \sqrt{\left(\frac{\sigma_3}{S_3}\right)^2 + \frac{(\tau_{31}^2)+(\tau_{23}^2)}{T^2}} \quad (1)$$

where

σ_3 = tensile stress,

τ_{31} & τ_{23} = shear stresses,

S_3 = Interlaminar tensile strength (composites),
Flatwise Tensile strength (adhesives),

T = Interlaminar shear strength (composites),
Shear strength (adhesives).

The 1, 2, and 3 subscripts represent the axes of the plies. The first, 1, represents the local x direction. The second, 2, represents the local y direction, and the third, 3, represents the local z direction. In the case of the composite plies, fibers run in the 1-2 plane. The third direction, 3, is perpendicular to this plane.

The failure index is a random variable. The probability of failure of the structure is the probability of the failure index being greater than 1.0. The distribution of the pull-off load at failure was determined computationally, and compared with experimental results. This is a basic change in the way the failure is viewed, with respect to more conventional design practices. In conventional design, factors of safety on applied loads and reduced property allowables for structural material strengths are built into all aspects of the structural calculations. These tend to mask or sidestep the uncertainties included in the various contributors to the failure calculations. Unfortunately, in conventional margins of safety calculations, all insight is lost into how the actual failure numbers should vary over a production population. Typically, the lack of insight demands that the full-scale articles must be subjected to extensive testing, with extra load built in to account for the accumulated uncertainties. Conversely, probabilistic methods-based design is geared to study the uncertainties, starting at the basic levels such as this bonded joint, as illustrated by the following evaluation.

Failure in the joint can be caused by failure in any of the locations: skin, left or right flanges, nugget, or the adhesive. The results indicate that failure of the joint at 75 degrees is governed by failure in the flange. The nugget does have a small contribution to the system probability of failure, but was not included here. The probability results are shown in Table 2 below, and the probability density function is shown in Figure 3.

Table 2 Probablity Results for Cobonded Joint Test Structure

Load	Pf
300	0.0002
325	0.006
350	0.079
360	0.119
372	0.238
385	0.348
400	0.559
405	0.587
410	0.607

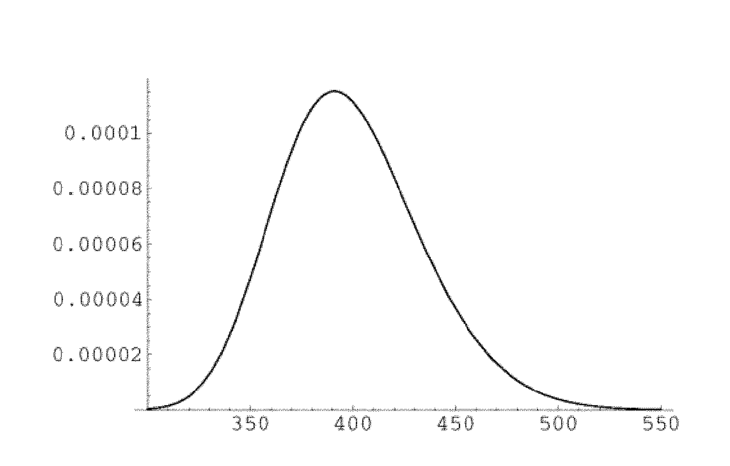

Figure 3 Probability Density Function of Pull-Off Load

Table 3 shows the comparison between the predicted (computational) and experimental results for the failure load. The results indicate the predicted spread in the failure load is much larger than that obtained by test. The most likely reason for this is the scatter used for the random variables during the computations is much larger than that experienced by the test articles. This highlights a fundamental difference that testing support for probabilistic methods-based design should demand.

Table 3 Comparison of Computational and Experimental Results

	Experimental*	Computational
COV (%)	2.15	8.02

*Based on three test results

The test articles are manufactured as a single structure, from a single batch of adhesive, tape, and cloth, then sectioned into three test articles, whereas the scatter used for the random variables is obtained from material, over several years. The scatter is unknown for a single batch of the materials tested. It is comforting, however, that scatter from the computational results is of the same magnitude, and larger than the test results. A smaller scatter would indicate a problem with either the computational model or the random variable inputs.

One important conclusion is that one should obtain statistics for the variables of the test articles in order to calibrate computational and experimental results. In addition, some processes of building-block test programs might be displaced by probabilistic analysis, thereby reducing test complexity and cycle time. This can result in significant savings of cost and time, during the development process.

The sensitivity factors, in terms of the change in probability with respect to a change in the mean or standard deviation of the random variables, are given in Table 4 below. Insight into these sensitivities is one of the major benefits of design procedures based on probabilistic methods. These sensitivities are by-products of the processes of building the functional-based probability density functions, but provide major insight into the robustness and weaknesses of the design process, at each level of progression towards the full structure analysis.

The sensitivities are normalized and given in percent. The results indicate the tape thickness, nugget radius, cloth tensile, and cloth shear strengths are important variables, with tape thickness being the most dominant. The nugget radius is a manufacturing issue, and the others are material performance issues. The large values of the important sensitivities, such as tape thickness, indicate which design variables are most influential in preventing failure of the structure being developed.

Table 4 Sensitivity Results for Cobonded Joint Test Structure*

Random Variable	dprob/dmean (Normalized %)	dprob/dstdev (Normalized %)
Cloth E1	1.0	0.1
Cloth E2	0.2	0
Cloth G12	0	0
Cloth Nu12	0	0
Cloth Thick	3.1	0
Tape E1	2.1	0
Tape E2	0.1	0
Tape G12	0.4	0
Tape NU12	0	0
Tape Thick	**50.7**	**55.6**
Adhesive Goct	1.5	1.5
Adhesive Tau-ult	0	0
Adhesive Gam-ult	0	0
Adhesive Thickness	0	0
Nugget Radius	**26.4**	**5.9**
Cloth Interlaminar Tensile Strength	**7.7**	**14.2**
Cloth Interlaminar Shear Strength	**6.9**	**22.6**
Tape Interlaminar Tensile Strength	0	0
Tape Interlaminar Shear Strength	0	0
Adhesive Shear Strength	0	0

* Corresponding to a load of 300 lbs./in.

Development of Analyses of Assemblies and Complete Structure

Analyses of the collection of basic elements of the structure that form the models for the large assemblies, and ultimately the complete aircraft structure, will ultimately provide the basis for accepting the structure is safe for flight. While some larger article testing will be desired, the costs of these articles will make untenable the testing of a population of them necessary to experimentally define their probability of failure. Thus, when the design reaches the level of complexity of this class of analyses, the basic probabilistic characterization of their structural capability will rely on the roll-up or buildup of probabilities of the smaller elements, as just examined. The following represents the large model probabilistic design evaluations that are expected at the culmination of structural design, wherein the acceptance for flight is primarily based on analyses that have good smaller element testing.

The wing structure to be considered, from which the basic blade joint structural element of the previous section was derived, is that shown in Figure 1. Specifically, the following analysis focuses on the wing structural box covers, or wing skins, and their performance when subjected to a defining load condition that puts this skin in a highly compressive stress state. This is a lightweight composite wing structure with syncore sandwich stiffened wing skins, and was chosen for analysis due to its criticality in flight performance, flight safety, and cost. The analysis focused on the cobonded joint, which attaches the wing box lower cover to the wing spars. Variations in material properties were explored to assess the reliability of the wing at the critical wing-spar interface, and to determine the important material inputs.

The specific design case is the highest down-bending limit load case, and was chosen since it gave the greatest deflection of the wing for all of the down-bending cases. The lower wing skin is the principle structure to be examined because skins and flanges were bonded together on the lower wing skin; the upper surface of the wing skin was bolted to the substructure.

The finite element model of the wing skin is shown in Figure 4, and the deformed model is shown in Figure 5. The fuselage and the outer wing were not included in the model, but were simulated using interface loads applied to the inner wing model using the freebody option in PATRAN. The removal of elements saved on computation time for results not needed in those areas.

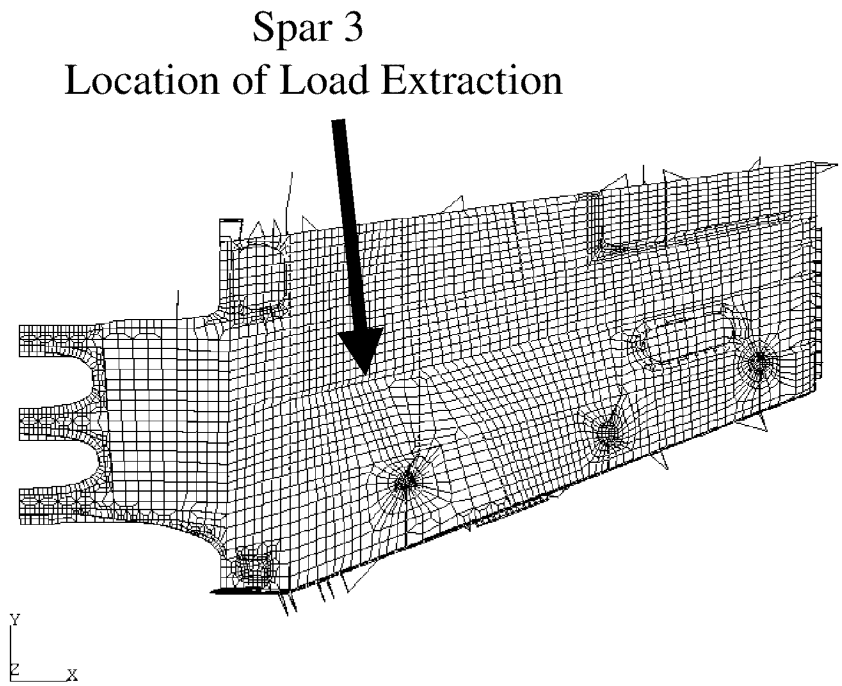

Figure 4 NASTRAN Wing Model

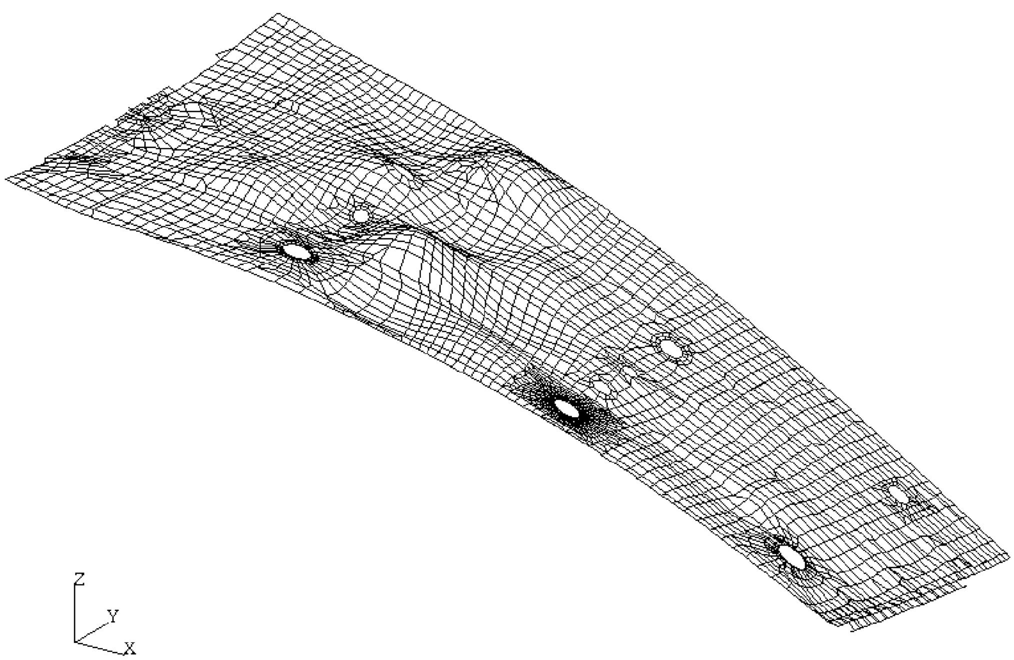

Figure 5 Deformation Plot of Wing Model at Ten Times Actual Deflection

The critical areas of the lower wing consisted of laminated composite material. Each of these laminates had multiple plies varying in orientation. However, the lay-up orientations were not varied for this probabilistic analysis; only variations in material properties were considered.

A structural analysis model has been developed that couples a global post-buckled wing analysis with a local blade analysis. This represents the high degree of complexity that is needed in the large-model probabilistic evaluations for failure. NASTRAN is used for the wing analysis, and BLADEM/THELMA is used for the local blade analysis.

A sequence of steps in the analysis procedure is shown in Table 5 below, and summarized in Figure 6. The steps are repeated each time NESSUS™ requires a deterministic solution. In Figure 6, bdf refers to NASTRAN bulk data file and op2 refers to the NASTRAN output 2 file. FREEBODY.EXE is a code developed by Boeing that converts NASTRAN freebody output loads into BLADEM/THELMA loads. Failure is predicted computationally when the failure index exceeds 1.0, as shown in equation 1.

Table 5 Wing-Blade Analysis Procedure

1)	Run NESSUS to generate input files for the wing NASTRAN model and the BLADEM model.
2)	Run PATRAN to generate detailed input file for NASTRAN. This inputs the correct material properties for the composite tape and cloth into the database.
3)	Run a geometric non-linear NASTRAN analysis to generate stresses, strains, and deformations of the wing structure.
4)	Run PATRAN to extract displacements from the large-scale wing model and place the displacements on the small section of the wing model that encompasses the blade region.
5)	Run NASTRAN on this small model to obtain freebody forces, using a geometrically linear run (freebody forces are not available in non-linear NASTRAN models).
6)	Run PATRAN to extract the results from NASTRAN.
7)	Run FREEBODY.EXE to convert the NASTRAN output loads to BLADEM/THELMA loads.
8)	Run the BLADEM/THELMA Model to solve for stresses/strains on a fine-meshed detailed model of the blade.
9)	Read the BLADEM/THELMA results back into NESSUS, and compute the failure index. Exclude regions near the boundaries of the blade to avoid boundary condition effects.

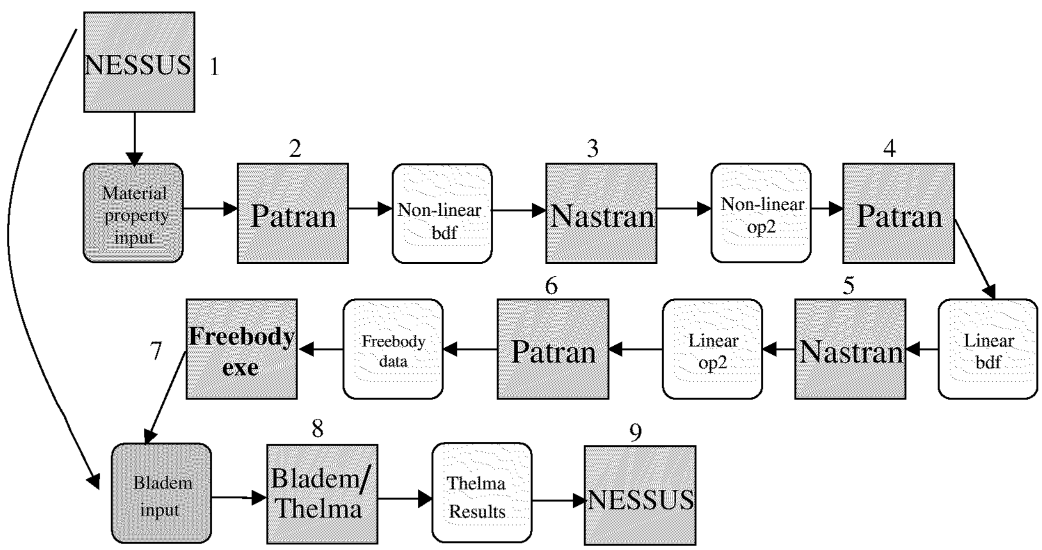

Figure 6 Wing-Blade Analysis Procedure

The random variables considered in this analysis are shown in Table 6. There are 18 independent random variables. Values are for 75 degrees Fahrenheit. Variables in italics are dependent variables.

Two different composite tapes were used. Tape 1, designated "Tape" in Table 6, was used only in the skins. Tape 2 was used to calculate properties in the cloth flange plies.

Table 6 Random Variables for Wing-Blade Analysis

#	Mat'l	Variable	COV (%)	Distribution*
1	Tape	Modulus of elasticity - E1 (tension & compression)	1.3	TNORM
2	Tape	Modulus of elasticity - E2 (tension & compression)	4.5	TNORM
	Tape	*Modulus of elasticity - E3 (= E2)*		
3	Tape	Shear modulus - G12 (tension & compression)	2.7	TNORM
	Tape	*Shear modulus - G23 (tension & compression) = E2/(2*(1+Nu23))*		
	Tape	*Shear modulus – G13 (tension & compression) = G12 = G31*		
4	Tape	Poisson's ratio – Nu12	5.1	TNORM
	Tape	*Poisson's ratio – Nu23 = 0.3*		
	Tape	*Poisson's ratio – Nu31 (=E2*Nu12/E1)*		
5	Cloth	Modulus of elasticity - E1	5.8	TNORM
6	Cloth	Modulus of elasticity - E2	6.2	TNORM
7	Cloth	Modulus of elasticity - E3	6.2	TNORM
8	Cloth	Shear modulus - G12	1.8	TNORM
9	Cloth	Shear modulus - G23	2.2	TNORM
	Cloth	*Shear modulus - G31 (=G23)*		
10	Cloth	Poisson's ratio – Nu12	62.5	LOGNORMAL
11	Cloth	Poisson's ratio – Nu23	7.3	TNORM
12	Tape 2	Modulus of elasticity - E1 (Cloth Nu31 = E3*Nu23/E1 Tape 2)	2.7	TNORM
13	Adhesive	Modulus of elasticity – E	9.1	TNORM
14	Adhesive	Shear modulus – G	9.1	TNORM
15	Tape	Interlaminar Tensile Strength	6.1	TNORM
16	Tape	Interlaminar Shear Strength	4.7	TNORM
17	Cloth	Interlaminar Tensile Strength	6.9	TNORM
18	Cloth	Interlaminar Shear Strength	8.2	TNORM

*TNORM = truncated normal (at $\pm 3\sigma$)

The structural deformation of the blade using the nominal (mean) values for the random variables is discussed in this section. The deformed structure of the local blade model is shown in Figure 7.

Figure 7 Deformed Blade Structure

A stress plot of the critical sigma 3 tensile stress component and the high stressed region is shown in Figure 8.

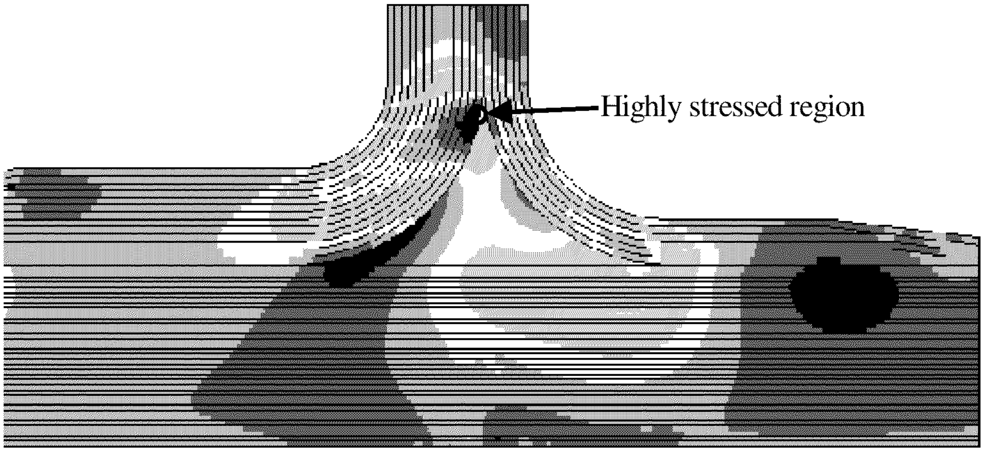

Figure 8 Sigma 3 Blade Results

Probability of failure calculations were performed for the major structural components of the blade (nugget, adhesive, skin plies, left and right flange plies). Table 7 below summarizes the results. The largest probability of failure is in the first ply of the left flange, at the high stressed region shown in Figure 8. This probability is denoted Ω. The probabilities of failure in the other locations of the blade are shown relative to Ω.

Table 7 Probability of Failure Results for Blade Locations

Blade Region	Probability of Failure Relative to Ω
Adhesive	0.0
Nugget	0.0
Skin Plies (1-35)	0.0
Left Flange	
Ply 1	1.0 (Ω)
Ply 2	0.53
Ply 3	0.32
Ply 4	0.22
Ply 5	0.08
Ply 6	0.05
Right Flange	
Ply 1	0.07
Ply 2	1.7E-4

A by-product of the probabilistic algorithm used to determine the probability of failure is deterministic sensitivity results. NESSUS™ computes a first order Taylor series expansion of the Failure Index, with respect to the random variables, e.g.,

$$FI \cong a_0 + \sum_{i=1}^{N} a_i X_i^* \qquad (2)$$

where a_0 and a_i are the coefficients determined from the analysis, and X_i^* are the random variables values about which the Taylor series is computed. In effect, the Taylor series coefficients are the deterministic sensitivity factors, e.g., $a_i = \left.\frac{\partial FI}{\partial X_i}\right|_{X_i^*}$.

The relative importance of each random variable can be determined from the equation

$$\gamma_i = \frac{a_i X_i^*}{\sum_{j=1}^{N} a_j X_j^*}, \tag{3}$$

then normalized such that the largest value of γ_i equals one. The values indicate the relative change in FI due to a change in random variable *i*. The normalized sensitivities are shown in Table 8.

Table 8 Deterministic Sensitivities

Random Variable	**Normalized Sensitivity**	**ΔFI/ΔRV**
Tape E1	0.09	-0.08
Tape E2	0.03	-0.03
Tape G12	0.11	-0.11
Tape Nu12	0.05	-0.05
Cloth E1	0.18	-0.18
Cloth E2	**-0.49**	**0.47**
Cloth E3	-0.11	0.11
Cloth G12	-0.02	0.02
Cloth G23	-0.22	0.21
Cloth Nu12	0.00	0.00
Cloth Nu23	-0.01	0.01
Cloth Nu31	0.00	0.00
Adhesive E	0.00	0.00
Adhesive G	-0.07	0.07
Interlaminar Tape Tensile Strength	0.00	0.00
Interlaminar Tape Shear Strength	0.00	0.00
Interlaminar Cloth Tensile Strength	**1.00**	**-0.97**
Interlaminar Cloth Shear Strength	0.00	0.00

Another sensitivity study is to assess the percent change in FI, given a percent change in each random variable, for example, 1%. That is, compute

$$\frac{\Delta FI}{\Delta X_i} * (1\% X_i). \tag{4}$$

The third column of Table 9 gives the results, which indicate that a 1% change in the cloth tensile strength yields approximately a 1% drop in FI. The negative sign on the cloth tensile strength indicates that an increase in its value yields a decrease in FI. The sensitivities clearly show the cloth interlaminar tensile strength is the dominant variable, with the Cloth E2 variable also important, followed by the Cloth G23 variable.

Probabilistic sensitivities consider both the deterministic sensitivities and the scatter of the random variable. These results can be used to determine the expected changes in the probability of failure, due to modifications in the mean value or standard deviation of the random variables. The results shown in Table 9 are similar to the deterministic sensitivities, and clearly indicate the Failure Index is most sensitive to the mean value and standard deviation of the cloth tensile strength, and somewhat sensitive to the Cloth E2 variable.

Table 9 Probabilistic Sensitivity Factors for Left Flange 1st Ply

Random Variable	d prob/ d mean	Normalized (%)	d prob/ d stddev	Normalized (%)
Tape E1	-1.77E-08	1	-3.35E-10	0
Tape E2	-1.21E-07	0	-2.07E-09	0
Tape G12	-7.47E-07	1	-1.17E-08	0
Tape Nu12	-7.52E-01	0	-1.13E-02	0
Cloth E1	-1.02E-07	2	-3.76E-09	0
Cloth E2	**2.76E-07**	**17**	**-2.85E-08**	**5**
Cloth E3	4.13E-07	1	-6.47E-09	0
Cloth G12	1.23E-07	0	-2.89E-09	0
Cloth G23	1.50E-06	4	-2.96E-08	0
Cloth Nu12	2.97E-01	0	-1.05E-01	0
Cloth Nu23	2.45E-01	0	-4.70E-03	0
Cloth Nu31	-9.37E-10	0	-1.55E-10	0
Adhesive E	1.46E-07	0	-6.36E-09	0
Adhesive G	6.21E-06	0	-1.56E-07	0
Interlaminar Tape Tensile Strength	2.21E-12	0	-1.64E-06	0
Interlaminar Tape Shear Strength	9.96E-14	0	-1.12E-07	0
Interlaminar Cloth Tensile Strength	**-8.15E-04**	**74**	**-1.88E-04**	**95**
Interlaminar Cloth Shear Strength	-2.17E-07	0	-8.77E-08	0

One can assess the reduction in the probability of failure as the failure index is modified and, also, how much must one decrease the failure index to lower the probability of failure to a target value. A study was performed, using the solutions of the left flange first ply. The study assumes the sensitivity of the failure index to the random variables remains constant, but the constant term, i.e., a_0 is reduced. This approach is easy to do, and does not require any additional finite element solutions.

The results are shown in Table 10, again relative to a probability of failure Ω. The results indicate that a 20% reduction in the failure index leads to a reduction in the failure probability of 300 times. Using this information, the designer can determine appropriate deterministically-based design targets of the failure index.

Table 10 Probability of Failure as a Function of the Failure Index

FI	Probability of Failure Relative to Ω
1.0	1.0 (Ω)
0.95	0.57
0.9	0.22
0.85	0.05
0.8	3.3E-3
0.7	1.7E-6

A system reliability analysis, considering failure in all locations and plies of the blade, was completed. In other words, the probability of failure of the blade is defined as failure of any location of the blade. The locations considered were adhesive, nugget, left flange, skin, and right flange. Failure in all plies was considered.

The system reliability is determined mathematically as

$$
\begin{aligned}
&P[blade] = P[failure\ \ in\ any\ region] = \\
&P[F_{nugget} \cup F_{adhesive} \cup F_{SkinPly1} \cdots \cup F_{SkinPlyN} \cup \\
&F_{LeftFlangePly1} \cdots \cup F_{LeftFlangePlyN} \cup \\
&F_{RightFlangePly1} \cdots \cup F_{RightFlangePlyN}]
\end{aligned}
\tag{5}
$$

where the symbol $\cup$ denotes a "union" of events.

The system reliability methodology used makes no assumptions regarding the independence or correlation of the failure locations. The analysis uses Monte Carlo or Importance Sampling, using the approximate limit state derived during the component probability calculations.

The results indicate that the failure modes are fully correlated. That is, failure will always occur first in the left flange 1st ply, for any realization of random variables. For example, there are no situations where failure will occur in the second ply of the left flange without already having failed in the first ply of the left flange. Therefore, the probability of failure of the blade *is* the probability of failure of the left flange 1st ply.

The probability of failure results of the blade, i.e., Ω, was larger than desired. As such, a redesign of the wing-blade was undertaken. A series of modifications to the design was carried out. The quality of the redesign was estimated deterministically by examining the computed failure index, using nominal values of the random variables. After a good candidate was discovered from these deterministic analyses, a probabilistic analysis was run to assess the probability of failure.

Three modifications were found that significantly reduced the failure index, two involved a geometric quantity, and one involved a material property. The modifications were to eliminate one ply layer from the right flange, to increase the nugget radius, and to reduce the Young's modulus of the cloth in the 2 direction, i.e., the E2 variable. The random variable statistics for E2 were modified such that the mean value was one-half its previous value, and the COV was unchanged. The importance of the magnitude in nugget radius can be seen in the sensitivities shown in Table 4.

The softening of the spar, by reducing E2 of the cloth, reduced the loads and moments in the wing. This, in turn, lowered the failure index. The knowledge that a significant reduction in the failure index could be

obtained by modifying E2 of the cloth and changing the nugget radius was discovered by evaluating the probabilistic sensitivity factors, i.e., Table 9 and Table 4. This information would not be straightforward to determine, without the sensitivity analyses. It may not be possible to implement this solution in an actual aircraft, as softening the spar may have adverse effects on wing stiffness and aeroelastic performance. Nevertheless, the design trade identifies a simple approach to significantly increasing safety for such a wing. Informed managers, aware of the consequences, can make the appropriate decision.

The distribution of the failure index for the redesign is shown in Figure 9. The mean failure index equals 0.6835, the standard deviation equals 0.049, and the probability of failure is less than 10^{-30}. Thus, the probability of failure of the wing blade was reduced many orders of magnitude, to approximately zero.

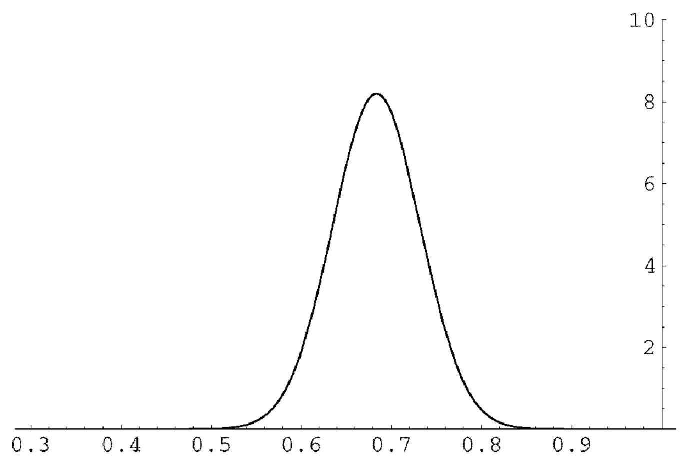

Figure 9 Probability Density Function of the Failure Index after Redesign

Observations for Reliance on Analyses for Acceptance

The details of key elements of a state-of-the-art composite wing airframe were used to identify and explore issues arising from an approach relying primarily on analysis for acceptance of airframe structure. A centerpiece of the analysis process, identified as needed for this reliance, is the application of probabilistic methods to the design and analysis process. The approach used was to develop high confidence in analysis of small pieces of the problem, and then building a large and complex analysis from these building blocks. In this, the approach taken is similar to the iterative design/test approach currently in common use. This roll-up of complexity allowed the uncertainties of the large analysis to be developed from those developed in the smaller and simpler analyses. The performance of the post-buckled wing box cover relied on a local model of the cobonded joint modeling the attachment of the wing box cover to the wing spars. The failure margin of the cobonded joint, whether it is thought of in terms of reliability or margin of safety, was critical to the structural safety of the wing. In this way, the buildup from simple analysis models to the final complex models needed for design acceptance was represented.

The analysis of the cobonded joint test article revealed a coefficient of variation of the pull-off load several times larger than that computed from three test results. The larger scatter predicted is most likely due to the fact that the scatter used for the material properties in the analysis was larger than the scatter found among the three test articles. This is because the test articles are manufactured as one structure, from one batch of materials, then sectioned. The material properties used in the analysis, however, were based on statistics of material properties collected over several years. This study reinforced the fact that realistic statistics of the random variables representing their variations expected over the production runs of the full structure be used in the test articles and in the probabilistic analysis, in order to accurately correlate calculations with tests.

This is significant because it indicates that using traditional element tests may not give a reliable prediction of the production population. Traditionally, strong measures are taken to assure maximum uniformity in the test articles. If one relies solely on pull-off tests from the same batch of material, then the actual population may have a larger scatter, making the results unconservative. Therefore, the use of probabilistic methods can anticipate variabilities for joints when it is not affordable to run the number of tests necessary to characterize all the effects of independent parameters that enter into this analysis. Thus, even in the small element stages of analysis buildup, the use of realistic design variable variations in a vigorous probabilistic design process should produce basic analyses that are equal to but likely better than what limited testing can suggest.

The probabilistic analyses of the structure described in this effort demonstrate that a new approach is available, one that allows safe prediction of the structural performance of these types of structural elements from basic data sets that can be used without retest, as the design evolves. That is, the variability in performance of basic structural elements due to the combined variations of material properties, manufacturing processes, and environmental effects are analytically predictable, based on experimental building blocks of the basic elements. This permits the testing of classes of elements to be considerably reduced or eliminated, and some retests that arise from geometry, manufacturing process, or material change may be eliminated. Cycle time for future programs is likely to be reduced by a substantial amount. An additional benefit could be a more effective design, as detail improvements thought of after initial testing may be more effectively implemented. This same benefit may eventually apply to the introduction of design changes in production or service.

A global-local probabilistic analysis of the wing-blade structure was performed to quantify the probability of failure, and to identify the random variables to modify that would most cost-effectively achieve a safer structure. Based on these findings, a redesign was carried out. In this case, two geometric and one material property change were sufficient to reduce the probability of failure by many orders of magnitude, such that the probability of failure of the redesigned structure is, basically, zero. Recognize that this design guidance provided a better design than could have been achieved by attempting to guide the redesign by limited testing.

For the larger analysis model of the wing, observations can be taken that reflect how complete structure would be treated. Traditional methods of acceptance rely on scaled-up loading of single test articles, to determine if the structure is adequate for its expected use. Variations and unexpected loadings are accounted for in the up-scaling of the loading. If probability of failure (POF) methods are used for acceptance, typically the analyses are used to project POF values, and the testing establishes the adequacy of the analyses. These are fundamentally different programs, with different conclusions to be drawn.

If POF analysis methods are used for acceptance, the degree of change in the way aircraft structure would be developed cannot be underestimated. The conclusions, in general, focus on the fundamental change in philosophy that every design variable must be represented by a distribution, rather than a single value. All the methods, then, must account for this. Note that the fundamental response analyses do not change. Force will always be equal to mass times acceleration; force will always equal to stiffness times deflection. However, over the production run of an aircraft structure, its stiffness will vary some, and the forces applied to it will vary some. Thus, its deflections will vary some. These variations cannot be captured by traditional test methods for acceptance, and cannot be exploited for improved overall design performance.

Design acceptability is measured by an acceptable probability of performance. POF approaches require probabilistic design methods to be useful analytical tools. It appears there are cost and schedule benefits from probabilistic design, when it is evaluated with the entire program taken as a whole. The ability to eliminate some testing, avoid some retesting, and define design refinements, using the sensitivity analyses, should make the probabilistic design approach less expensive and faster in the long run, and provide the high confidence analysis needed for structural acceptance.

Testing plays a different role with this approach. Testing provides distributions in how the design variables may vary, but the real change is that hardware testing is aimed more at refining the analyses than certifying the structure is safe. Safety evaluations through POF define structural safety. This fundamental change is the

largest and most pervasive change in the structural design process, and dictates much of the following observations.

While the same analysis models used in deterministic approaches are also used with probabilistic design approaches, the analysis steps in probabilistic design are much more demanding than before. Where, before, the response of a configuration was calculated to determine if selected values of the design variables provided adequate strength, in probabilistic design there are ranges and distributions of these variables. This means that in the simplest deterministic approaches, a multitude of response evaluations are required based on the important combinations of the design variables. Fortunately, the probabilistic analysis tools have evolved to a degree where the multiplicity of these evaluations is minimized. Still, there are many more evaluations with probabilistic methods.

The probabilistic analysis process demands more skills than the traditional deterministic approaches of the design engineer. Higher resolution response analyses are used earlier in the design cycle, often requiring insight into such subjects as nonlinear, temperature dependant procedures. The nonlinear buckling response example of the wing may be more typical than past experience would suggest. In fact, this investigation suggests that a good team for design would consist of engineers familiar with best modeling schemes to produce high quality idealizations. They would complement more traditional structural engineers, who have great insight into structural solutions for new aircraft configurations. Added to these engineers would be engineers who have a focus on the basic mechanics of probabilistic analyses, models, and statistics. Each of these members brings needed depth to the design process that may not have been needed before.

While identifying the problem areas and extremely sensitive design variables may be easier with probabilistic methods, the selection of the corrective or improving modification may rely on traditional approaches. These would likely be evaluated using deterministic methods to define the selection of a nominal value for the modified design value that needed changing. In this effort, for example, the selection of general direction of change in the design variables identified by sensitivities was first examined with deterministic dry runs. Once the correct direction is identified, these new values can be examined to determine if they are successful, using the probabilistic methods.

The large amount of data required to perform these response evaluations, and the equally large volume of results, highlight the data management challenges associated with probabilistic methods. Where once there existed single assumed values for the design variables, now there are many. Where once there existed a single response prediction, now there are many. This is further complicated by the fact that in building from simple models/analyses to complex ones, it is important to assure the correct distributions are passed on to the next level of analysis complexity. This suggests that some of the deterministic procedure-based structural optimization codes may still be useful in identifying design solutions for problems identified with probabilistic methods.

More detailed information is needed for the design process, and this information is needed earlier in the process. Material value distributions are needed at the outset. Geometry variations are needed before any geometry variations can be measured. While this implies that more is then known about the design, it occurs at a time when little can be known in some area because it is just being conceived. Thus, reliance on design information databases that document past histories in the distributions of materials and geometries become crucial. However, this means someone must be willing to invest in gathering and storing this information after the design is set and has been sold. It is important that the integrity of the data be ensured, as is the case in present deterministic analysis approaches. More use of online database management systems that can be used to better ensure data integrity and consistency is certainly in order.

There are long-term implications built into this data. Changes or improvements in manufacturing processes or material capabilities must be addressed with reanalysis of the probabilistic results, since assumed improvements in any single factor may not always combine in a beneficial way. It also means that testing must include the realistic changes that should be expected over a long production run with different suppliers

of the materials and process hardware. This was illustrated with the results of the local blade stiffener calculations. The analysis of the cobonded joint test article revealed a coefficient of variation of the pull-off load several times larger than that computed from three test results. The predicted larger scatter is due to several differences between the model and the way the test specimens were manufactured. The test articles were manufactured as one structure, from one batch of materials, and then sectioned into three specimens. As a result, the test did not reflect the full variability of the material properties that would be seen between different batches of material, nor did it reflect the differences in geometry that would be present between different manufacturing runs.

Early design insight is greater and more complete with the probabilistic approach. The sensitivity analyses available with probabilistic analyses are of great value in many ways. They can tell you what variables are important, which ones must be held to close tolerances, where detailed testing is needed, and can suggest which variables can greatly improve the performance of the structure with little or non-obvious changes. The insight to soften the E2 values of the composite cloth in the blade is a prime example of the latter. Without the insight of the sensitivity studies available in the new method, this design solution most likely would not have been examined.

There appears to be the opportunity to tailor the POF of all the components of a structure to provide a better risk balance and, thus, remove unnecessary overdesign. Since the building-block approach forms up the POF of each component from those elements it is made of, probabilistic design offers the ability to tailor these building blocks so that all contribute equally to the overall POF. It also allows the designer to better identify the crucial elements needing design attention.

With greater specificity in the way a structure fails, by knowing the probability of each failure mode, the designer can work toward supplying more graceful failure modes for the structure. This "leak before massive rupture" structural response can be most useful in saving aircraft from sudden catastrophic failure modes that provide little warning or opportunity to safely return.

The testing approach outlined here in support of probabilistic design is changed, fundamentally, from traditional approaches. More details are needed early, but testing done on other programs using similar materials and fabrication methods can provide much of that. The detail of the measurements taken for a range of loads is much greater than the traditional method of determining rupture loads. Subcritical strain and deflection data are key to fine-tuning analysis models. The probabilistic analyses allow safe prediction of the structural performance of these types of structural elements from basic data sets that can be used without retest, as the design evolves. That is, the variability in performance of basic structural elements due to the combined variations of material properties, manufacturing processes, and environmental effects are analytically predictable, based on experimental building blocks of the basic elements.

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